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TRISO manufacturing process management using a control chart

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1. Introduction

TRISO fuel is a type of micro fuel particles. It consists of a fuel kernel in the center, coated with four layers of three isotropic materials. TRISO fuel particles are designed to not crack due to the stresses from processes (such as differential thermal expansion or fission gas pressure) at temperatures up to and beyond 1600°C, and therefore can contain the fuel in the worst of accident scenarios in a properly designed reactor. The TRISO fuel particles are fabricated into compacts and placed in a graphite block matrix in a prismatic block gas cooled reactor. TRISO fuel particles have been developed in the KAERI as part of the NHDD project. We expect the TRISO fuel compacts to be used in the Korean type VHTR reactor in the near future. Two of the major quality components are the sphericity and exact kernel size. Thus, we present a TRISO quality control method to improve the quality of TRISO and cope with continuous mass manufacturing production.

2. Methods and Results

In this section, some of the techniques used to detect the assignable cause are described.

2.1 Control charts

Quality has always been an integral part of virtually all products and services. However, our awareness of its importance and the introduction of formal methods for quality control improvement have undergone evolutionary development. In 1924, Walter A. Shewhart of Bell Lab developed a statistical control chart concept. A control chart is a very useful process monitoring technique. When unusual sources of variability are present, sample averages will plot outside the control limits. This is a signal that some investigation of the process should be made and corrective action to remove these unusual sources of variability taken. Systematic use of a control chart is an excellent way to reduce the variability. A typical control chart is shown in Fig. 1

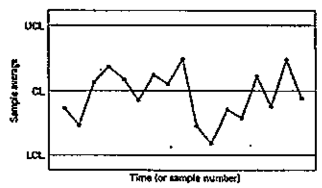

Fig. 1. Typical control chart example.

2.2 Economic control chart

Much of the research in the development of economic models of control charts has been devoted to the $\bar{X}$-control chart. We developed an economic model based on the surrogate variable for the optimum economic design of the $\bar{X}$-control chart Duncan proposed first in 1956 [1]. For a more specific presentation of the model, we describe underlying statistical assumptions as follows:

1. The process begins in the in-control state, with the mean and variance of the performance variable being μ_y and σ_y, respectively. An assignable cause occurs according to a Poisson process with an intensity of λ occurrences per unit time. If an assignable cause of magnitude c occurs, then the process mean shifts from μ_x to $\mu_x \pm c\sigma_x$
2. The surrogate variable X given Y=y is normally distributed with mean $\lambda_1 + \lambda_2 y$ and variance σ^2, where λ_1 and λ_2 are known constants. λ_2 is assumed to be positive, and thus X and Y have a positive linear relationship. It can be easily shown that (X, Y) follows a bivariate normal distribution with means $(\lambda_1 + \lambda_2\mu_y , \mu_y)$, variances $(\lambda_2\sigma_y^2 + \sigma^2, \sigma_y^2)$, and correlation coefficient $\rho = \lambda_2\sigma_y/(\lambda_2^2\sigma_y^2 + \sigma^2)^{1/2}$. [3]
3. The time taken to find an assignable cause is b_1' and the time required to eliminate it is b_1''. The time taken to identify a false alarm is b_2 and the time required to take and interpret a sample is b_3.
4. The cost for finding and eliminating an assignable cause is a_1, while the cost for identifying a false alarm is a_2' and the cost incurred from the lost production due to a false alarm is a_2''. In addition, the cost of sampling and testing for X variables is $a_3 + a_4 n_x$, where a_3 and a_4 are fixed and variable sampling costs, respectively, and n_x is the sample size. The net incomes per unit time of operation in the in-control and the out-of-control states are i_1 and i_2, respectively.

2.3. Monitoring Procedures

Based on the previous assumptions, we now develop a model for an $\bar{X}$-control chart using a surrogate variable. Let h denote the time interval between X samples, and let k_a and k_w, respectively, denote the action and warning limit factors for an $\bar{X}$-control chart. The factors k_a and k_w

establish the action and warning regions of an $\bar{X}$-control chart, respectively, delimited by $[(-\infty, \mu_x-k_a\sigma_{\bar{x}}), (\mu_x+k_a\sigma_{\bar{x}}, \infty)]$ and $[(\mu_x-k_a\sigma_{\bar{x}}, \mu_x-k_w\sigma_{\bar{x}}), (\mu_x+k_w\sigma_{\bar{x}}, \mu_x+k_a\sigma_{\bar{x}})]$ with $\sigma_{\bar{x}} = \sigma_x/\sqrt{n_x}$. If we define $Z_{\bar{x}} = \sqrt{n_x}(\bar{X}-\mu_x)/\sigma_x$, the proposed model can then be summarized as follows:

Step 1. Take a sample of size n_x after an interval of h time units.
Step 2. If $|Z_{\bar{x}}|<k_w$, go to step 1. Otherwise, go to step 3.
Step 3. If $|Z_{\bar{x}}|<k_a$, go to step 4. Otherwise, stop the process and go to step 4.
Step 4. If the alarm is false, go to step 1. Otherwise, go to step 5.
Step 5. Identify and eliminate the assignable cause. Go to step 1.

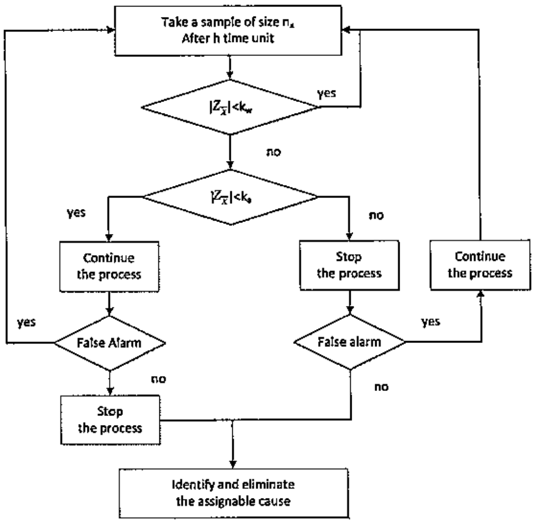

Fig 2. The monitoring procedure

2.4 Development of profit function and application

The expected cycle time and expected net income per cycle and can be derived as follows (1) and (2). We skipped the detailed derivation owing to a lack of space.

$$E(T) \approx \frac{1}{\lambda} + \frac{h}{p_a+p_w} - \tau + b_3 n_x + b_1' + b_1'' + \frac{\alpha_a b_2}{\lambda h}. (1)$$

$$E(I) \approx \frac{i_1}{\lambda} + i_2\left(\frac{h}{p_a+p_w} - \tau + b_3 n_x + \frac{p_w b_1'}{p_a+p_w}\right) - \frac{a_3+a_4 n_x}{h}\left(\frac{1}{\lambda} + \frac{h}{p_a+p_w} - \tau + b_3 n_x + \frac{p_w b_1'}{p_a+p_w}\right) - \left(a_1 + \frac{(\alpha_a+\alpha_w)a_2'}{\lambda h} + \frac{\alpha_a a_2''}{\lambda h}\right). (2)$$

It is important to obtain the exact figure of the fuel size for uniform production. When we measure the outer diameter of the TRISO fuel, we can use a method such as PSA, micrometer, and X-ray. Of the three methods, the use of an X-ray (Y, performance variable) is the most accurate, but the measurement equipment is too expensive to purchase. On the other hand, the PSA (X, surrogate variable) method is less precise owing to the scattering of light, but makes it easier to obtain data without emitting dangerous radiation.

From an actual data analysis [2], it is known that the mean and variance of Y are μ_y=1099.32 μm and $\sigma_y^2=(32.18\ \mu m)^2$, respectively, and the variance of X is $\sigma_x^2=(34.75\ \mu m)^2$. It is also known that X for the given Y=y is normally distributed with a mean of 100.41+0.86y μm and variance of 0.09 μm^2, and that the correlation coefficient between X and Y is ρ=0.799.

The following values for the cost and process parameters are assumed as follows: λ=0.05, c=2, i_1=100, i_2=0, a_1=200, a_2'=200, a_2''=200, a_3=3, a_4=1.5, b_1'=10, b_1''=10, b_2=25, and b_3=0.3 from Panagos *et al* [4]

Table I shows that the economic model using the surrogate variable yields a 9% higher expected net income per hour than the economic model using the performance variable.

Table I: Optimum design results

Parameter	Economic Model (performance variable)	Economic Model (Surrogate variable)
n_x (n_y)	6	4
h	3.927	3.163
k_w	1.979	2.550
k_a	3.479	3.493
E(T)	45.731	43.472
E(I')/E(T)	43.735	46.006
E(C₁)/E(T)	2.235	1.775
E(C₂)/E(T)	5.450	4.928
E(A)	36.050	39.303

3. Conclusions

We proposed an economic design of an $\bar{X}$-control chart based on the surrogate variable for a case in which using the performance variable is impossible or inappropriate. Compared with the control chart based on the performance variable, the proposed model gives a larger long-run expected net income per unit of time if the correlation between the performance variable and the surrogate variable is relatively high. The proposed model can be applied to the VSI (Variable Sampling Interval) control chart

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